



# Energy Storage for Aerospace Applications

Marla E. Pérez-Davis, Patricia L. Loyselle, Mark A. Hoberecht,  
Michelle A. Manzo, Lisa L. Kohout, and Kenneth A. Burke  
Glenn Research Center, Cleveland, Ohio

Carlos R. Cabrera  
University of Puerto Rico, Rio Piedras, Puerto Rico

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Prepared for the  
36th Intersociety Energy Conversion Engineering Conference  
cosponsored by the ASME, IEEE, AIChE, ANS, SAE, and AIAA  
Savannah, Georgia, July 29–August 2, 2001

National Aeronautics and  
Space Administration

Glenn Research Center

## Acknowledgments

The authors would like to acknowledge Mr. Paul Prokopius and Dr. Lawrence Thaller for their help in providing information on the historical background of fuel cell and battery development at the NASA Glenn Research Center.

Available from

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Hanover, MD 21076

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## IECEC2001–AT–08

### ENERGY STORAGE FOR AEROSPACE APPLICATIONS

Marla E. Pérez-Davis  
NASA Glenn Research Center

Lisa L. Kohout  
NASA Glenn Research Center

Patricia L. Loyselle  
NASA Glenn Research Center

Michelle A. Manzo  
NASA Glenn Research Center

Kenneth A. Burke  
NASA Glenn Research Center

Mark A. Hoberecht  
NASA Glenn Research Center

Carlos R. Cabrera  
University of Puerto Rico, Rio Piedras, Puerto Rico

#### ABSTRACT

The NASA Glenn Research Center (GRC) has long been a major contributor to the development and application of energy storage technologies for NASA's missions and programs. NASA GRC has supported technology efforts for the advancement of batteries and fuel cells. The Electrochemistry Branch at NASA GRC continues to play a critical role in the development and application of energy storage technologies, in collaboration with other NASA centers, government agencies, industry and academia.

This paper describes the work in batteries and fuel cell technologies at the NASA Glenn Research Center. It covers a number of systems required to ensure that NASA's needs for a wide variety of systems are met. Some of the topics covered are lithium-based batteries, proton exchange membrane (PEM) fuel cells, and nanotechnology activities. With the advances of the past years, we begin the 21<sup>st</sup> century with new technical challenges and opportunities as we develop enabling technologies for batteries and fuel cells for aerospace applications.

#### INTRODUCTION

Over the past three decades, the Electrochemistry Branch of the NASA Glenn Research Center (GRC) has been a major contributor to the development and application of advanced battery and fuel cell systems for NASA missions and programs. The demand for terrestrial-based systems in the 70's prompted work in the area of battery systems for electric vehicles, alkaline fuel cell technology for the Shuttle, and fuel cells for large-scale powerplant applications. As the work

became more focused toward aerospace applications in the 80's and 90's, NASA GRC became involved in the development of nickel-hydrogen batteries for low earth orbit (LEO) and geosynchronous orbit (GEO) spacecraft and PEM fuel cell technology for high altitude aircraft. Today, the Electrochemistry Branch at NASA GRC continues to play a critical role in the development and application of energy storage technologies, in collaboration with other NASA centers, government agencies, industry and academia.

#### BATTERY TECHNOLOGY

The NASA Glenn Research Center has a long history of contributing to the development of battery storage systems for both aerospace and terrestrial applications. Early efforts focused on the development and support of nickel-cadmium, silver-zinc, silver-hydrogen and hydrogen-oxygen battery systems. Hydrides were investigated as a means to store hydrogen for both battery and fuel cell systems. In the 1970's NASA GRC conducted a Department of Energy (DoE)-funded electric vehicle effort. Work focused on the development and evaluation of nickel-zinc and lead acid battery systems for electric vehicles. The culmination of this effort was the successful demonstration of a GRC-designed battery powered automobile.

As support for the terrestrial related energy programs diminished in the 1980's, efforts became more focused on aerospace-related applications. The battery team at GRC became involved in the development of nickel-hydrogen technology for aerospace applications. Many of the GRC-initiated advances, including the use of 26% KOH and

catalyzed wall-wicks, are routinely incorporated into today's aerospace cells [1]. In addition, GRC conducted both in-house and contractual efforts that demonstrated the feasibility of bipolar nickel-hydrogen battery designs with the potential to reduce mass and volume by addressing battery requirements at the system level [2]. Parallel efforts at improving the specific energy and energy density of nickel-hydrogen systems focused on the development of a light-weight nickel electrode. Replacement of the traditional sintered substrate used in nickel electrodes with a light-weight, highly porous nickel felt significantly reduces the weight of a nickel-hydrogen cell [3]. Throughout the 70's and 80's, GRC conducted parallel separator development programs aimed at replacing the asbestos material used in both fuel cells and alkaline battery systems. There were extensive efforts aimed at separator development for zinc based systems as well. This separator expertise was later applied to nickel-hydrogen and nickel-cadmium systems in the 80's and 90's and culminated with the publication of a manual outlining standard test procedures for evaluating separator materials for alkaline cells [4].

Today, the efforts of the Electrochemistry Branch at GRC are focused on supporting NASA's current and future needs for rechargeable batteries for a wide variety of aerospace applications. Current applications cover a wide range of performance requirements. These include planetary missions, such as landers and rovers, that require batteries ranging in capacity from 6-35 ampere-hours, that are capable of operating at temperatures as low as  $-20^{\circ}\text{C}$  following the long stand times associated with travel to the mission destination; LEO spacecraft and planetary orbiters that require 30,000-50,000 cycles over a five to ten year period; GEO spacecraft that have an operating life greater than fifteen years; and aircraft applications that require high voltage (28-300V) and high capacity (50-100 AH) batteries that can operate from  $-40^{\circ}\text{C}$  to  $+60^{\circ}\text{C}$ . Further, these batteries are required to meet the stringent environmental requirements associated with flight applications such as vibration, shock, and high impact.

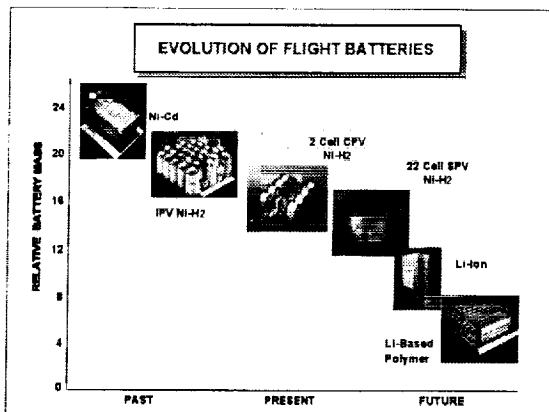


Figure 1: Evolution of Flight Batteries

The evolution of flight batteries over time is illustrated in Figure 1. As technology advances the systems are becoming more lightweight with increased cycle and performance capabilities. Nickel-cadmium batteries have served as the workhorse system since NASA's earliest missions. In recent years, they have been replaced with nickel-hydrogen systems. These systems are capable of operating at deeper depths-of-discharge while providing comparable life to nickel-cadmium systems thus resulting in a lighter-weight energy storage option. Improvements to the existing chemistries and cell designs can yield lighter, more compact and longer-lived systems. For future battery applications, lithium-based battery systems offer the potential of lighter weight, less complexity, and higher performance. Lithium-based batteries offer >2.5X improvement in specific energy over state-of-the-art nickel-hydrogen batteries. Advanced lithium-based batteries will operate over a much wider temperature range and reduce power system mass and volume while decreasing the cost, thus increasing mission capabilities and enabling many future missions. The most challenging goals for the lithium-based battery system are to develop batteries with improved energy density and specific energy that are capable of long calendar life required for GEO and long cycle life required for LEO applications.

The wide range of requirements for future NASA missions cannot presently be met by a single battery chemistry. In order to address NASA's near and far term battery system requirements, the battery-related programs at GRC address multiple systems covering a wide range of technology readiness levels.

#### Battery Technology Development

The majority of NASA's near-term (<5 yrs) missions will be using nickel-based battery systems. Current efforts at GRC that support the development of nickel-based batteries include the development of a bipolar nickel-metal hydride battery, via a contracted effort with Electro Energy Incorporated [5], and the demonstration of scaled-up light-weight nickel-electrode technology in flight hardware.

In order to address the next generation (3-8 yrs) of secondary batteries for future aerospace missions, a joint Department of Defense (DoD)/NASA program has been established to develop lithium-ion batteries with the capabilities required by future NASA and DoD missions. The objectives of this program are to: 1) develop high specific energy and long cycle life lithium-ion cells and batteries; 2) establish production sources; and 3) demonstrate technology readiness for a variety of applications, such as rovers and landers, LEO and GEO missions, aviation/unmanned aerial vehicles, and military terrestrial applications. The technical approach involves: a) development of advanced electrode materials and electrolytes to achieve improved low temperature performance

and cycle life; b) optimization of cell design to achieve high specific energy; c) development of cells (6-100 Ah) and batteries (16-300 V) of various sizes required for various future missions; and d) the development of control electronics for smart battery management. These batteries will be initially used in missions where weight and volume are critical and cycle life requirements are low to moderate (200-1000).

NASA's far-term (6-12 yrs) battery requirements will be met by the development of lithium-based polymer electrolyte batteries. This development is supported by a new battery initiative at GRC known as the Polymer Energy Rechargeable Systems (PERS) Program. These lithium-based batteries have the potential to offer five times the energy of conventional energy storage at 1/3 mass, 1/10 volume, and 1/3 cost. In addition, the system is leak-free and non-toxic. The cells are flexible and conformable, making them ideal candidates for many diverse applications, including spacecraft, unmanned aerial vehicles, portable wireless electronics and electric vehicles. A combination of contracted and in-house efforts has been initiated that presently focuses on the development and evaluation of the various polymer electrolytes as well as cathodes, anodes and related support elements.

The Electrochemistry Branch is also investigating the application of nanotechnology to advanced battery systems and advanced battery concepts that incorporate thin-film solid state devices and conducting polymer electrodes.

#### NASA Aerospace Flight Battery Program

In addition to the technology development efforts, GRC leads the NASA Aerospace Flight Battery Systems Program, an agency-wide effort aimed at ensuring the quality, safety, reliability, and performance of flight battery systems for NASA missions. The program supports the development of guidelines, documents, and procedures related to diagnostic techniques developed for identifying failure modes. In addition, it supports the establishment and maintenance of a central database to serve as the repository for battery characterization and verification test data that supports the validation of battery technologies for flight use, as well as modeling efforts aimed at predicting performance of aerospace battery systems. The majority of the program resources are dedicated to the testing and validation of aerospace design nickel-cadmium, nickel-hydrogen, nickel-metal hydride, and lithium-ion secondary battery systems. There are also significant efforts characterizing and validating commercial off-the-shelf secondary battery technologies for use in manned missions. The program also addresses the issues related to the safety and reliability of primary lithium battery systems used in manned space operations [6].

#### Mission Support

In addition to the technology development activities discussed above, the Electrochemistry Branch is supporting the evaluation of flight battery technologies for the International Space Station and the electric auxiliary power unit (EAPU) replacement for the Space Shuttle. GRC's role in support of nickel-hydrogen technology has largely centered on the evaluation of multiple nickel-hydrogen cell design options from various vendors. More than 475 cells have been tested as part of this effort. The majority of the testing has been conducted at the Naval Surface Warfare Center (NSWC), Crane Division with a smaller proportion being conducted in-house at GRC [7]. These efforts culminated with the launch of the first nickel-hydrogen batteries for the ISS in November of 2000.

#### **FUEL CELL TECHNOLOGY**

The NASA Glenn Research Center has long been a major contributor to the development and application of fuel cell technologies for NASA's missions and programs. In the 70's, NASA GRC was responsible for advancing the state of fuel cell technology to a level which qualified it for the Shuttle on-board power system. Parallel technology advancement programs on the Gemini proton exchange membrane (PEM) fuel cell and the Apollo alkaline fuel cell were conducted at GRC. These were a combination of GRC in-house and contractual fuel cell R&D efforts. When the alkaline technology was selected for Shuttle, an optimized alkaline cell and stack technology was provided to the NASA Johnson Space Center (JSC) for Shuttle system development. GRC continued to support the JSC system development effort to the mid-80's by working to improve the life and performance of the Shuttle alkaline fuel cell technology [8].

In the 80's, NASA GRC culminated management of the DoE/Gas Research Institute Phosphoric Acid Fuel Cell Program for a 40 kW powerplant field test, stack and the balance-of-plant technology development for 200 kW, 7.5 MW, and 11 MW powerplants [9]. During this period, GRC also examined regenerative fuel cell (RFC) concepts for Lunar/Mars applications in support of the Space Exploration Initiative [10]. On the automotive side, GRC conducted a study of the feasibility of using a PEM fuel cell in an electric vehicle as part of the DoE-funded electric vehicle program. This study was one of the initial guiding elements in what has become the very large PEM fuel cell program for electric vehicles. As a result of this work, NASA GRC was tasked to lead the team to produce DoE's 10-year Fuel Cells for Transportation Plan in the early 1990's [11]. Moreover, GRC continued to address the RFC PEM concept for Space Station, high altitude balloon [12], and high altitude aircraft applications during the 90's.

Today, NASA GRC continues its involvement in the development of PEM fuel cell and regenerative fuel cell systems for a wide variety of applications, including earth-based and planetary aircraft, spacecraft, planetary surface power, and terrestrial use. The GRC fuel cell team is currently participating in the development of technologies to reduce CO<sub>2</sub> emissions from civil transport aircraft. The concepts under investigation involve the conversion of the propulsion systems to hydrogen fuel and the introduction of new energy conversion technologies, i.e. air-breathing fuel cells, to produce an environmentally benign, low cost and durable system for aircraft propulsion. GRC is involved in the system-level design and analysis of the fuel cell systems, which range in power from 100 kW to 90 MW. In addition, NASA GRC is developing and intends to demonstrate revolutionary energy conversion technologies to achieve reduced emissions aircraft operations. The focus of this program is on far-term, breakthrough technologies. The overall approach is a multidisciplinary effort to develop a revolutionary, non-traditional fuel cell power/propulsion system for aircraft applications. Areas under investigation include cell chemistries, advanced materials, and novel cell, stack, component and system designs.

For space vehicle applications, PEM fuel cell technology offers major advantages over existing alkaline fuel cell technology, including enhanced safety, longer life, lower weight, improved reliability and maintainability, higher peak-to-nominal power capability, compatibility with propulsion-grade reactants, and the potential for significantly lower costs. A team comprised of NASA GRC, NASA Marshall Space Flight Center, and Honeywell [13] (formerly AlliedSignal Aerospace) has just completed the development of modular PEM fuel cell stack technology for use in future reusable launch vehicles. Small substacks as well as a prototype 5.25 kW modular PEM fuel cell stack have been successfully built and operated. This 5.25 kW stack is shown in Figure 2.

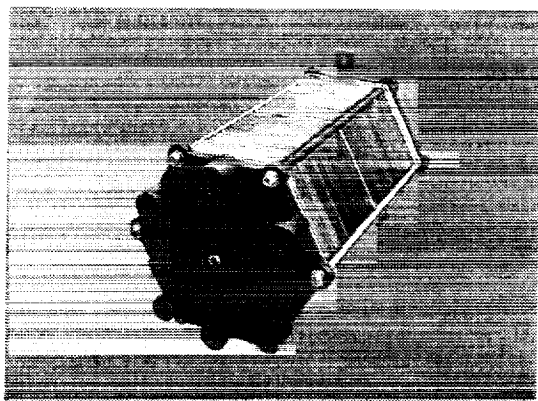


Figure 2: Honeywell Prototype 5.25 kW PEM Fuel Cell Stack for Reusable Launch Vehicle Applications

In addition, NASA GRC, NASA Johnson Space Center, NASA Kennedy Space Center, and NASA Marshall Space Flight Center have just begun a 5-year PEM fuel cell powerplant development program that will culminate in the delivery to NASA of an engineering model PEM fuel cell powerplant for test and evaluation. A modular approach to powerplant design that relies on commonality with commercial hardware will allow NASA to leverage the evolving and highly competitive automotive and residential markets in PEM fuel cell technology, assuring technology transfer and low costs well into the future.

GRC is also involved in the development of passive ancillary component technology to be teamed with a hydrogen-oxygen unitized regenerative fuel cell (URFC) stack to form a revolutionary new RFC storage system for aerospace applications. Replacement of active RFC ancillary components with passive components minimizes parasitic power losses and allows the RFC to operate as a H<sub>2</sub>/O<sub>2</sub> battery. The goal of this program is to demonstrate an integrated passive 1 kW URFC system.

## NANOTECHNOLOGIES

Recently, advances in the area of nanotechnology have developed materials and techniques which could significantly improve the performance, mass, and volume of energy conversion/storage devices.

Carbon nanotubes have exhibited many interesting properties including electrical properties that range from conducting to insulating, exceptionally high mechanical strength, and a potential to store large amounts of hydrogen and other atoms and molecules within the tubes and tube bundles. Because of these unique properties, energy conversion/storage devices incorporating nanotubes have the potential to display significant improvements in performance and energy density over the current state-of-the-art [14, 15, 16, 17].

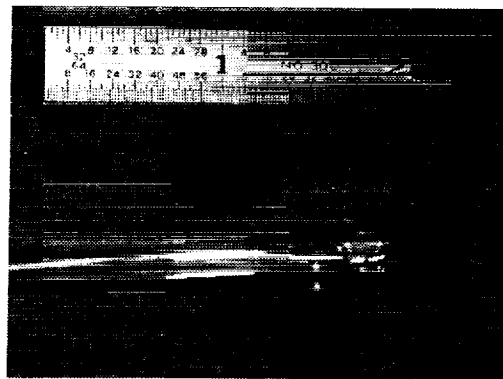


Figure 3: GRC Research Electrodes Made From Carbon Nanotubes



Currently, the NASA Glenn Research Center is assessing the technical feasibility of utilizing carbon nanotubes and nanotechnologies in future energy storage systems designs with initial investigations focusing on their capacity to reversibly store hydrogen under various conditions. An electrode made at GRC from carbon nanotubes is shown in Figure 3. This electrode is being used to evaluate the electrochemical properties of nanotubes with respect to hydrogen absorption.

## CONCLUDING REMARKS

In summary, the Electrochemistry Branch at the NASA Glenn Research Center continues to play a critical role in the development and application of battery and fuel cell technologies, in collaboration with other NASA centers, government agencies, industry and academia. With the advances of the past years, we begin the 21<sup>st</sup> century with new technical challenges and opportunities as we develop enabling battery and fuel cell-based technologies for aerospace power and propulsion systems.

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE July 2001		3. REPORT TYPE AND DATES COVERED Technical Memorandum
4. TITLE AND SUBTITLE  Energy Storage for Aerospace Applications			5. FUNDING NUMBERS  WU-755-A4-08-00	
6. AUTHOR(S) Marla E. Pérez-Davis, Patricia L. Loyselle, Mark A. Hoberecht, Michelle A. Manzo, Lisa L. Kohout, Kenneth A. Burke, and Carlos R. Cabrera				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER  E-12904	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER  NASA TM-2001-211068 IECEC2001-AT-08	
11. SUPPLEMENTARY NOTES Prepared for the 36th Intersociety Energy Conversion Engineering Conference cosponsored by the ASME, IEEE, AIChE, ANS, SAE, and AIAA, Savannah, Georgia, July 29-August 2, 2001. Marla E. Pérez-Davis, Patricia L. Loyselle, Mark A. Hoberecht, Michelle A. Manzo, Lisa L. Kohout, and Kenneth A. Burke, NASA Glenn Research Center; and Carlos R. Cabrera, University of Puerto Rico, Rio Piedras, Puerto Rico 00931. Responsible person, Marla E. Pérez-Davis, organization code 5420, 216-433-6755.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Categories: 44, 20, and 07 Available electronically at <a href="http://gltrs.grc.nasa.gov/GLTRS">http://gltrs.grc.nasa.gov/GLTRS</a> This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  The NASA Glenn Research Center (GRC) has long been a major contributor to the development and application of energy storage technologies for NASA's missions and programs. NASA GRC has supported technology efforts for the advancement of batteries and fuel cells. The Electrochemistry Branch at NASA GRC continues to play a critical role in the development and application of energy storage technologies, in collaboration with other NASA centers, government agencies, industry and academia. This paper describes the work in batteries and fuel cell technologies at the NASA Glenn Research Center. It covers a number of systems required to ensure that NASA's needs for a wide variety of systems are met. Some of the topics covered are lithium-based batteries, proton exchange membrane (PEM) fuel cells, and nanotechnology activities. With the advances of the past years, we begin the 21st century with new technical challenges and opportunities as we develop enabling technologies for batteries and fuel cells for aerospace applications.				
14. SUBJECT TERMS  Energy storage; Aerospace; Fuel cells; Batteries; Nanotechnologies			15. NUMBER OF PAGES 11	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	